

Will the LHC Look into the Fate of the Universe?*

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The LHC will probe the nature of the vacuum that determines the properties of particles and the forces between them. Of particular importance is the fact that our current theories allow the Universe to be trapped in a metastable vacuum, which may decay in the distant future, changing the nature of matter. This could be the case in the Standard Model if the LHC finds the Higgs boson to be light. Supersymmetry is one favoured extension of the Standard Model which one might invoke to try to avoid such instability. However, many supersymmetric models are also condemned to vacuum decay for different reasons. The LHC will be able to distinguish between different supersymmetric models, thereby testing the stability of the vacuum, and foretelling the fate of the Universe.

According to quantum physics, what we see as particles are really excitations out of the “vacuum”. The precise configuration of the vacuum, in particular its symmetries, are determined by the fact that the Universe seeks to minimize its energy. The symmetries of the vacuum then determine the fundamental forces acting on matter, i.e., the three “gauge” forces (electromagnetic, weak and strong) and gravity.

Although the laws of physics appear to be constant today, the vacuum need not be inert on cosmological timescales: it can occasionally undergo dramatic shifts as, for example, quantum tunnelling of the Universe into a vacuum configuration with lower energy (cf. Fig. 1). The unstable but very long-lived vacua are called “metastable”. The eventual tunneling transition results in a new vacuum which has, in general, different symmetries and hence different fundamental forces. Vacuum shifts of this type are “phase transitions” – analogous to the boiling or freezing of water. In the particle physics context they are also known as “vacuum decay”.

One such symmetry-changing phase transition is thought to have happened shortly after the Big Bang. It is almost certain that at this stage there was a vacuum shift that “broke” the symmetry underlying the weak nuclear force causing it to freeze out so that it plays very little role in our everyday life. Earlier on, another phase transition may have been responsible for the present relative strength of the strong nuclear force, and an even earlier phase transition may have caused the emergence of space and time themselves. Has the vacuum now settled down, or will it change again? As we shall see, in our current best guesses about the next level of particle physics, the eventual decay of the vacuum is a very reasonable possibility. The LHC collider now being commissioned at CERN is designed to reach unprecedented high energy scales. It will be the first accelerator to probe

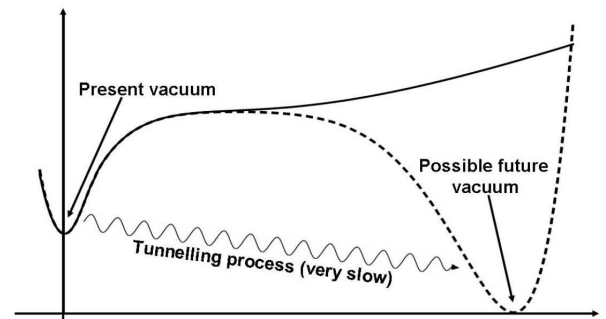


FIG. 1: Sketch of the potential energy. The solid line shows the potential in a theory with only one stable vacuum (i.e., a single minimum of the energy). The dashed line represents the potential in a slightly modified theory where there is an additional minimum of lower energy, so that the first “false” minimum is only metastable. In the latter theory, the Universe can undergo a phase transition where it eventually tunnels through the barrier and ends up in the “true” minimum of lower energy (wavy arrow). Since particles correspond to small excitations around a minimum, changing the minimum itself would correspond to a drastic change in particle properties. However, depending on the height and width of the barrier, this process can be extremely slow and may need many, many billions of years. Although the LHC will probe only a small region around the present minimum (and therefore can never trigger a crossing of the barrier), in many cases we may nevertheless be able to tell whether we live in a false vacuum.

directly the nature of the vacuum, and hence the possible fate of the Universe.

Within our current paradigm of particle physics, the Standard Model, vacuum decay could occur if the Higgs boson, the quantum excitation of the vacuum that manifests the breaking of its symmetry, is relatively light^{1,2}. A relatively light Higgs is even favoured indirectly by data from lower-energy accelerators³. Discovering the Higgs boson and accurately measuring its mass is one of the primary objectives of the LHC⁴. Hence, if the Standard

*This is a brief review targeted primarily at a non-expert audience.

Model is all there is, the LHC will tell us about the stability of its vacuum.

However, many expect more than just the Standard Model to be found at the LHC. One promising extension of the Standard Model is supersymmetry, and indeed this seemed a promising way to stabilize the vacuum⁵. However, recent developments^{6,7} suggest instead that supersymmetry may actually condemn the Universe to vacuum decay (for a precursor, see⁸). Again, the LHC may tell us whether Nature has this fate in store.

Supersymmetry⁹ is a symmetry that relates elementary particles of integer and half-integer spin, known as bosons and fermions, respectively. The Standard Model is not supersymmetric. Although it contains examples of both, bosons (e.g., gauge bosons such as photons which carry force, and the Higgs boson that gives particles their masses) and fermions (e.g., matter particles such as quarks and electrons) they are not related by any symmetry. In a supersymmetric extension of the Standard Model, every particle would acquire a superpartner whose properties such as charge and mass are exactly the same, and which differ only in their spin. For example, gauge bosons are accompanied by fermions called gauginos, and quarks are accompanied by bosons called squarks.

Supersymmetry provides a solution to profound conceptual problems of particle physics by taming certain infinities in the theory, and offers practical advantages such as a candidate for the dark matter that appears to be cluttering up the Universe¹⁰. For these reasons, many physicists expect it to play a significant role in Nature. However, at currently accessible energies no superpartners have been found. Our best guess is that supersymmetry is itself a broken symmetry much like the broken symmetry of the weak nuclear force – this could result in higher superpartner masses and explain why they have so far evaded detection, but would leave intact the nice mathematical properties which made supersymmetry so attractive in the first place. The LHC may well discover supersymmetry⁴, in particular if it provides the dark matter, as well as a light Higgs boson.

Even within the simplest supersymmetric version of the Standard Model (commonly called the Minimal Supersymmetric extension of the Standard Model or MSSM), a particular choice of supersymmetry breaking pattern can lead to an unstable vacuum. Generally, around half of the available parameter space of superpartner masses leads to metastable vacua. In this case the endpoint of the eventual decay would be a new vacuum with very little symmetry and hence practically no forces acting at all except gravity¹¹. The change in physics caused by these transitions would be drastic – in the new vacuum, atoms and nuclei would fall apart, and the Universe would become a soup of heavy, decoupled particles.

So far, metastability of the vacuum seems to be just a quirk of the theory, which could, in principle, be avoided in a sizeable part of parameter space. Recent developments however suggest that in large classes of supersym-

metric theories, metastability is essentially inevitable, and in fact the consistency of the theory requires it. The arguments hinge on one niggling issue with supersymmetry: it is hard (in a mathematical sense) to break it. As we shall see, if the breaking of supersymmetry is realised in one favoured way it is practically guaranteed that, in addition to the vacuum in which the Universe currently resides, there is another state of lower energy – often called the “true” vacuum – in which supersymmetry is unbroken (the present metastable vacuum is often referred to as a “false” vacuum). Everyday physics in false and true vacua is hard to distinguish, and in particular all the matter in the Universe we see today could very well be composed of elementary particles which are quantum excitations over a false vacuum, that is susceptible to decay to the true vacuum in which supersymmetry is an exact symmetry of Nature. Moreover, the alternative scenarios for supersymmetry breaking *also* offer future vacuum decay as a possibility, if not an inevitability. The LHC cannot trigger this change in the vacuum[†], but it can serve as a crystal ball that reveals the fate of the Universe.

The recent developments involve a rather subtle web of theoretical and experimental arguments, and so before we describe them we should (perhaps to cheer the reader up a little) discuss the timescales on which our present vacuum would decay, as indicated by the wavy line in Fig. 1. There is very firm evidence that the laws of physics have been constant since the first few minutes after the Big Bang. Thus, unless we are rather unlucky, one would expect that the timescale would be at least billions of years. However, we can do better than that: quantum mechanics allows us to compute the lifetimes of false vacua. The physics underlying false vacuum decay was elucidated in a beautiful series of papers by Coleman and de Luccia¹². They found that a false vacuum decays by creating huge instantaneous “lumps” of particles, called (appropriately enough) instantons, on which bubbles of the new vacuum nucleate. The effect of such a lump, and hence the rate of decay, increases with the strength of the interactions in the theory. For example, the simplest instantons, which are comprised of only gauge bosons, allow tunneling between different “gauge” vacua with a rate proportional to an exponentially small factor, $e^{-\frac{8\pi^2}{g^2}} \ll 1$, where g is the interaction strength. The important point is that it is the self-interaction of the gauge bosons (i.e. the fact that g is not zero) which allows transitions between different vacua. The decay of a false vacuum is catalyzed by analogous but more complicated instantons which interpolate across the energy barrier separating true and false vacua, and the forms of the energy barriers (in particular their heights and widths, cf. Fig. 1) determine the typical decay time. The probability of vacuum decay is al-

[†] If they could, cosmic-ray collisions would already have done so long ago¹³.

ways exponentially suppressed in this manner, and in all realistic models, this makes the supersymmetry-breaking false vacuum very long-lived, with a life expectancy much longer than the age of the Universe.

Let us now return to why we expect that metastability is unavoidable in certain well-defined and testable scenarios. This requires more information on how supersymmetry may be broken. In order to fit in with our current (lack of) observations, supersymmetry is almost certainly broken by what is known as a “hidden sector”. This is a part of the theory that interacts extremely weakly with the particles of the supersymmetric Standard Model – called in this context the “visible sector”. The supersymmetry breaking that ends up in the visible sector is filtered and weakened through these interactions, a process known as mediation. The models can be classified according to how the supersymmetry is broken in the hidden sector and how this breaking is mediated to the visible sector.

For example, the supersymmetry-breaking hidden sector could interact with the visible sector through gravitational interactions alone, the option known as gravity mediation. Since every particle interacts with gravity, this is the weakest sort of mediation one could imagine, and in these models the scale of supersymmetry breaking in the hidden sector has to be very high – the energy scales involved are roughly 10^{11} GeV (remember that the proton mass is about 1 GeV). An alternative scenario is that the supersymmetry-breaking hidden sector interacts with the visible sector through the other fundamental forces as well, i.e., the electroweak and strong gauge interactions. In this case the mediation is stronger and the scale of supersymmetry breaking in the hidden sector is correspondingly lower, typically 10^5 – 10^7 GeV.

What about the way that supersymmetry is broken? Either matter fields dominate the supersymmetry breaking¹⁴, the option known as F -term breaking, or gauge fields dominate¹⁵, the option known as D -term breaking. An important difference is that F -term breaking is calculable in the sense that we have full mathematical control, whereas D -term breaking is rather more difficult to handle – there are unknown factors that affect the size of supersymmetry breaking or indeed whether supersymmetry is broken at all. In order to be able to make firm conclusions here, therefore, we consider F -term breaking.

We represent the situation schematically in Fig. 2, where the main classes of supersymmetric models are depicted. The class of models that we consider primarily are the gauge-mediated models with F -term breaking – the scenario we refer to as ‘calculable gauge mediation’ (CGM). It is in these models that metastability is generically unavoidable as we shall now see. The LHC has the capability to tell us whether Nature realizes this option. Metastability may occur in the other scenarios as well, but may be avoidable, by for example a judicious choice of parameters. As we discuss at the end, in this case the LHC can also reveal whether Nature has chosen metastability.

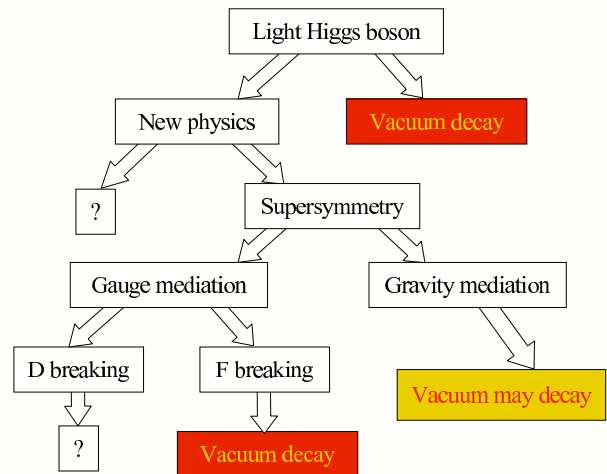


FIG. 2: The LHC may reveal the fate of the Universe by discovering a light Higgs boson and/or supersymmetry. In calculable gauge-mediated models of supersymmetry breaking the present vacuum is necessarily unstable, and the same may be true in gravity-mediated models.

The seeds of the inevitability of metastability in this class of models lie in an important theorem due to Nelson and Seiberg¹⁶, who identified a *necessary and sufficient* condition for F -term supersymmetry breaking. Called R -symmetry, this condition is a generalisation of the familiar rotations in space that is unique to supersymmetric theories. The problem arises because in R -symmetric theories the supersymmetric partners of the gauge bosons – called gauginos – must be massless, in conflict with experiments, which require $m_{\text{gaugino}} \gtrsim 100$ GeV. The dilemma is that non-vanishing gaugino masses require both supersymmetry breaking *and* R -symmetry breaking, but Nelson and Seiberg tell us that these two requirements are mutually exclusive. How to get around it?

There are two logical possibilities. One is to include in the theory a small, controlled amount of R -symmetry breaking. More precisely, the Lagrangian function, which defines all masses and interactions of the theory, would be of the form

$$\mathcal{L} = \mathcal{L}_R + \varepsilon \mathcal{L}_{R\text{-breaking}}, \quad (1)$$

where \mathcal{L}_R describes a theory which preserves R -symmetry and breaks supersymmetry, whereas $\mathcal{L}_{R\text{-breaking}}$ breaks R -symmetry, and ε is our small control parameter. When $\varepsilon = 0$, the lowest-energy (ground) state breaks supersymmetry, and there is no supersymmetric vacuum at all (solid line in Fig. 1), but the gauginos are massless. However, with a small $\varepsilon \neq 0$, R -symmetry is broken explicitly. In this case, the Nelson-Seiberg theorem requires that a supersymmetry-preserving vacuum appears in addition to the supersymmetry-breaking one (dashed line in Fig. 1), since the full theory breaks R -symmetry. It

is a general consequence of supersymmetry that any supersymmetric vacuum must be the state of lowest energy. Hence, the non-supersymmetric vacuum must be metastable. However, it is important to note that the two vacua are separated by a distance that goes to infinity as $\varepsilon \rightarrow 0$ (in Fig. 1 the new minimum moves further and further to the right). As the control parameter $\varepsilon \rightarrow 0$, the decay rate of our false vacuum becomes exponentially longer and longer.

The second possible way to obtain non-vanishing gaugino masses is for the vacuum itself to break the R -symmetry – a possibility known as spontaneous breaking. With spontaneous breaking, the whole theory still obeys the symmetry, but the effective physics we see in the symmetry breaking vacuum does not. Spontaneous (rather than explicit) breaking of R -symmetry does not introduce new supersymmetry preserving minima, and does not by itself make the supersymmetry breaking vacuum metastable. In particular we do not need to introduce and explain the origins of a very small parameter ε , as we had to with explicit breaking. At the same time, gauginos acquire masses proportional to the scale of spontaneous R -breaking.

Superficially then, it looks as if one might be able to avoid metastability. Alas, spontaneous symmetry breaking involves some subtleties: we begin with a symmetric theory and choose a vacuum that breaks it. But, since the original theory had a symmetry, so must the set of choices of possible vacua. In other words, there is a degeneracy of vacua all with the same energy, corresponding precisely to the symmetry we are breaking. Since small fluctuations in the choice of vacuum do not cost any energy, there must be a new massless particle – the Goldstone mode, that reflects this symmetry. In the case of spontaneously-broken R -symmetry, this particle is called the R -axion. In order to avoid astrophysical and experimental bounds, the R -axion must also acquire a mass, although the lower bounds on its mass are much weaker than those on the gaugino mass: $m_{R\text{-axion}} \gtrsim 100$ MeV, and therefore easier to fulfill. Nevertheless, its mass means that the original R -symmetry must itself be explicitly broken by very small effects, and according to the earlier arguments, this again implies that the vacuum is metastable. In this case, however, the gaugino mass is divorced from the size of the *explicit* R -breaking parameter ε , which now determines the R -axion mass instead. This exhausts the logical possibilities and shows that massive gauginos and massive R -axions imply metastability.

An invaluable contribution to these arguments was made by the recent papers of Intriligator, Seiberg and Shih (ISS)^{6,7}. In particular, the question that had previously been unanswered was how to generate a Lagrangian of the form (1). ISS discovered an extremely simple and beautiful class of supersymmetric models that generate dynamically a small R -breaking term of the required type by quantum effects, and hence lead to a long-lived metastable vacuum. The Nelson-Seiberg theorem manifests itself in a truly wonderful way in these theories: the

classical theory (i.e., before we add in quantum effects) has an exact R -symmetry. However, the quantum theory does not preserve the R -symmetry – the R -symmetry is said to be “anomalous”, which guarantees that small effects of the type $\varepsilon \mathcal{L}_{R\text{-breaking}}$ will appear. In the ISS models, ε is a naturally small parameter, because it too is generated by instanton-like effects and hence is proportional to the factor $e^{-8\pi^2/g^2} \ll 1$.

This breakthrough has led to a burst of activity building gauge-mediated models incorporating the ISS models as hidden sectors. The complementary explicit and spontaneous approaches to model-building were successfully incorporated with a few twists. In the first approach, the explicit R -breaking of the ISS models was not able to generate gaugino masses, so a second source of R -breaking was required. However, the smallness of this second term – necessary for the longevity of the metastable vacuum, turned out to be guaranteed within the ISS models if the R -symmetry-breaking effects were generated at a very large energy scale, e.g., the Planck scale¹⁷.

In the second approach, the gauginos are already massive and, as we discussed above, the job of the explicit R -breaking is merely to give the R -axion a small mass $m_{axion} \gtrsim 100$ MeV. The controlled quantum effects within all models of the ISS type are sufficient to do this, and remarkably simple versions of the ISS model could be found that led to the required spontaneous R breaking^{18,19}, so that gauginos receive sufficiently large masses $m_{\text{gaugino}} \gtrsim 100$ GeV. These are explicit, credible CGM models with metastable vacua. The LHC will be able to produce gauginos weighing an order of magnitude more than the present lower limit⁴, offering a good prospect of testing such metastable CGM scenarios.

We have argued that, in such CGM scenarios of supersymmetry breaking, metastability is generically unavoidable because gaugino and R -axion masses must both be non-zero. Until now, we have not addressed the problem of the cosmological constant: global supersymmetry breaking à la CGM always generates a large vacuum energy. This makes a contribution to the cosmological constant that is much larger than the observed tiny value.

This contribution can in principle be compensated in a “supergravity” theory, i.e., a theory combining supersymmetry with gravity, which can easily generate an additional negative contribution to the vacuum energy. Adding this contribution would not change our conclusions about the metastability of the vacuum in CGM models. However, supergravity does offer the alternative possibility of using gravitational-strength interactions to mediate supersymmetry breaking, as illustrated in Fig. 2. There is no theorem in such gravity-mediated models that our present vacuum is necessarily unstable. However, this is still a generic possibility¹¹, and the cosmology of such metastable gravity-mediated scenarios was discussed recently²⁰. These scenarios can also be probed by the LHC, through measurements of the spectrum of supersymmetric particles, should they be discovered.

Before closing, we address one question that may

have been nagging the reader: if our present vacuum is a “false” one, how did the Universe arrive in such a metastable minimum? Why did it not start directly in the “true” stable vacuum? In the models discussed above the reason is that the early Universe was (presumably) very hot. At high temperatures, what later became the metastable vacuum is preferred by entropy, and the Universe was automatically driven into it. Later, as the Universe cooled, it got trapped in the metastable state^{21,22,23} (for a precursor, see⁸).

In conclusion, we have argued that the present ground state of the Universe may well be temporary, and that it may ultimately decay into an energetically more

favourable one. This could arise in the Standard Model, for example, if the Higgs boson is light. One way to avoid this would be to postulate an extension of the Standard Model to include supersymmetry. However, the metastability of our present vacuum is also unavoidable in a generic class of supersymmetric theories. In either case, the LHC may be able to indicate whether Nature is metastable by for example discovering the Higgs boson and measuring its properties, or by discovering superpartners and measuring their masses. By studying the nature of the vacuum, the LHC will provide a unique window on the fate of the universe.

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